Radio detection of air showers with LOFAR

Cosmic Ray Key Science Project:

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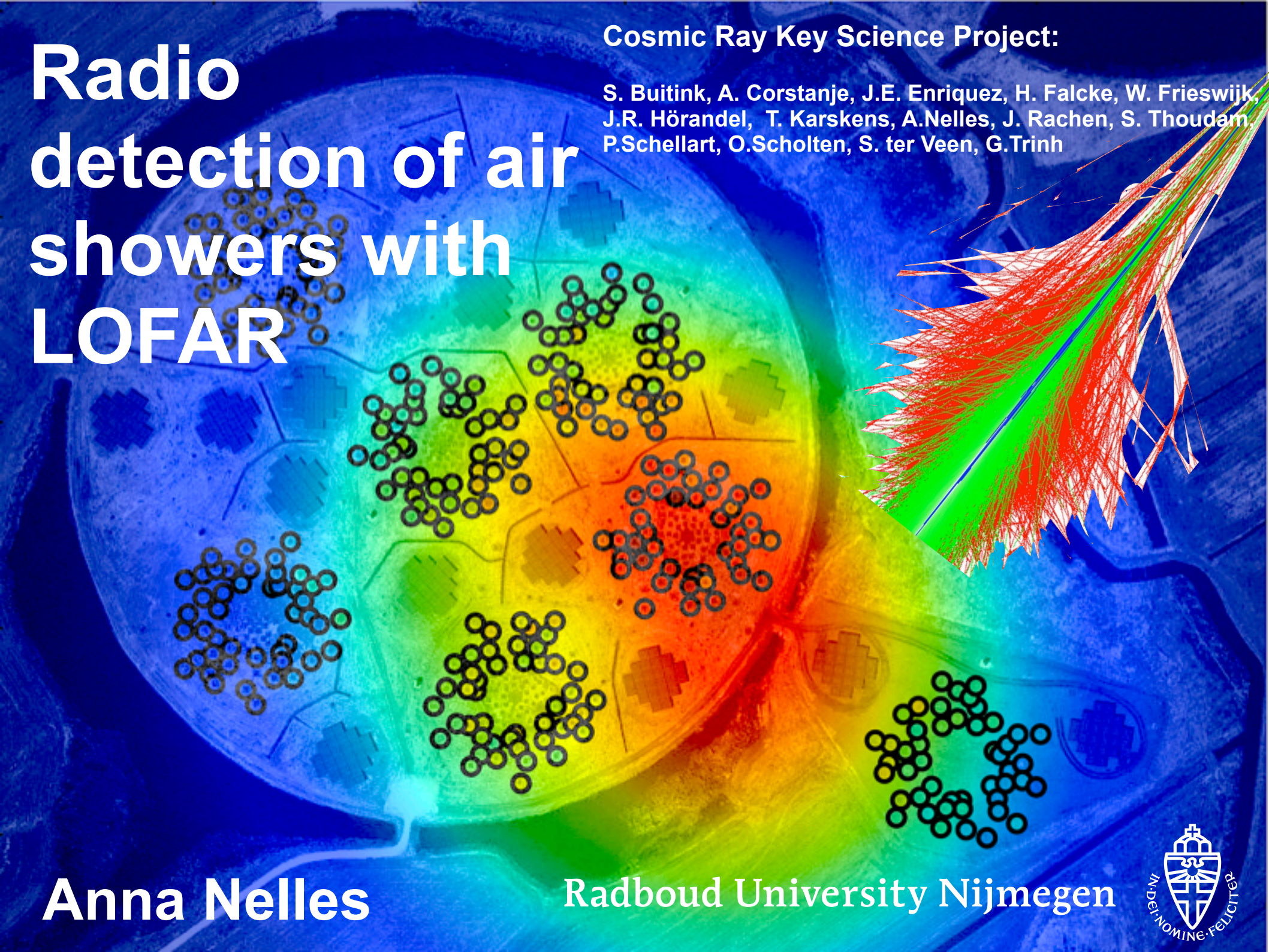

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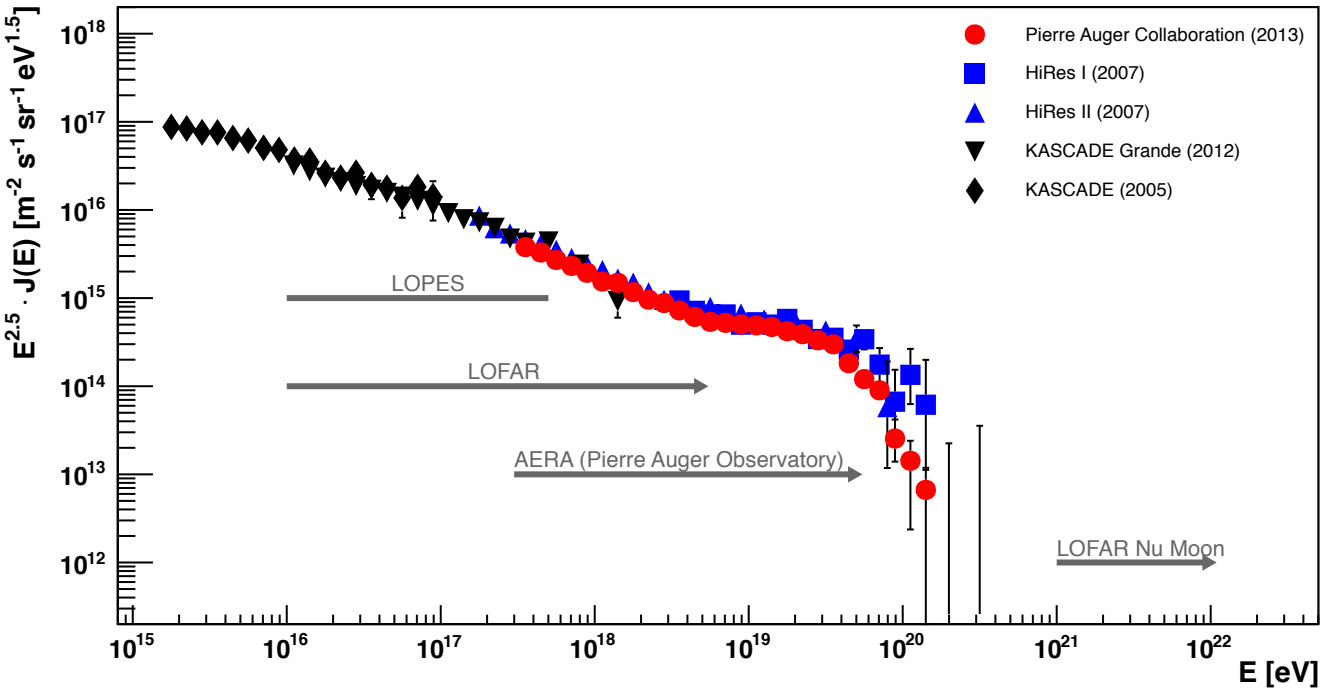
Why radio detection of cosmic rays?

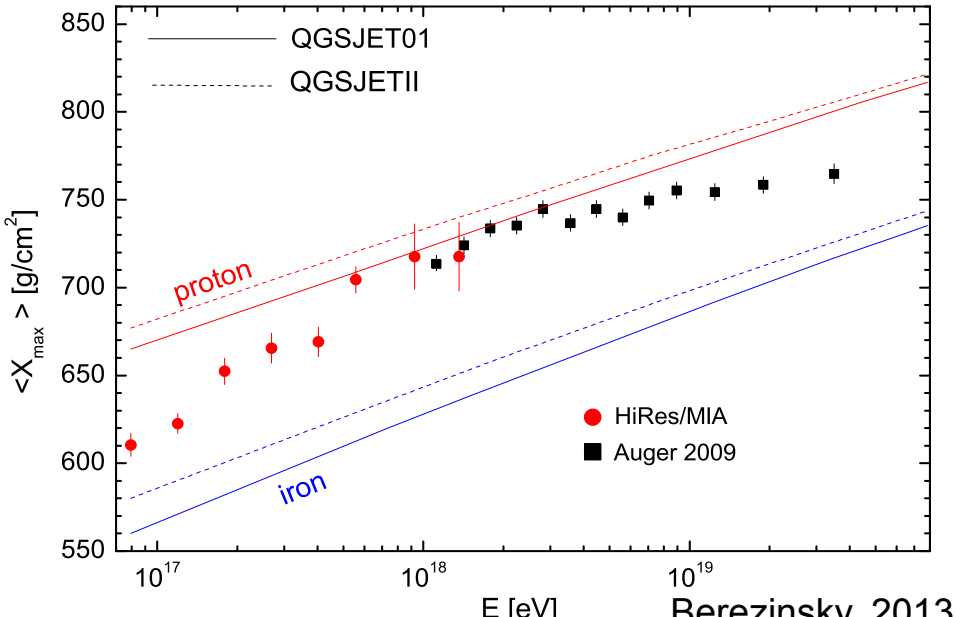


At the "End" of the spectrum:

- accelerators reach limit?
- propagation cut-off?
- transition of sources?
- sources still unknown

Key to answer question:

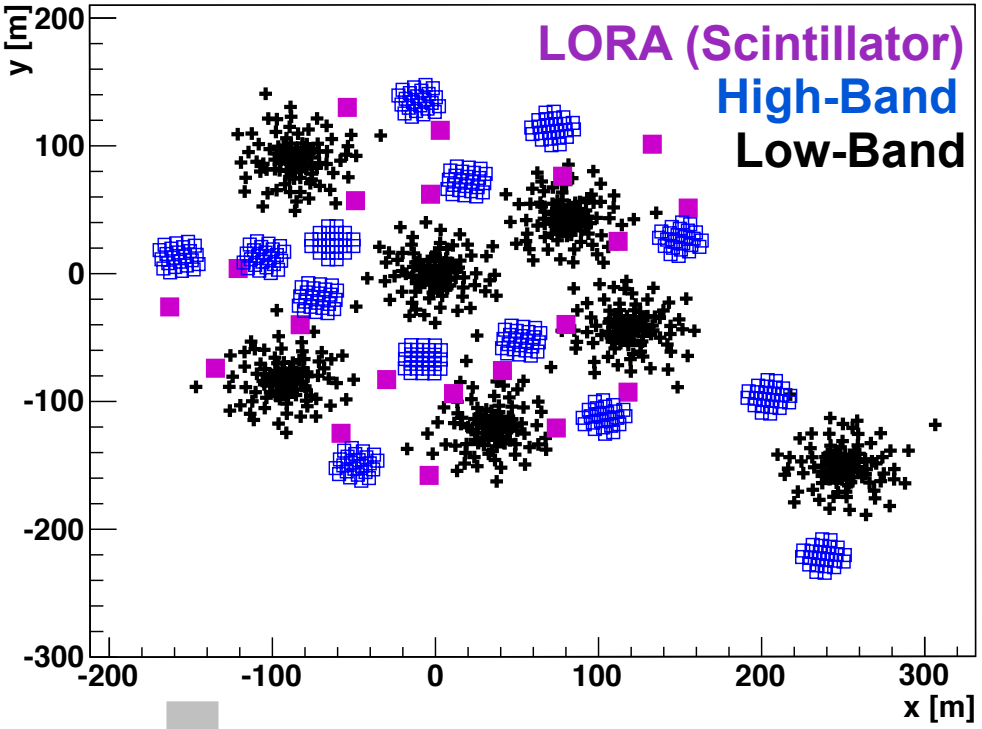
- large number of events, i.e. long duty-cycle
- information about mass of every air shower need

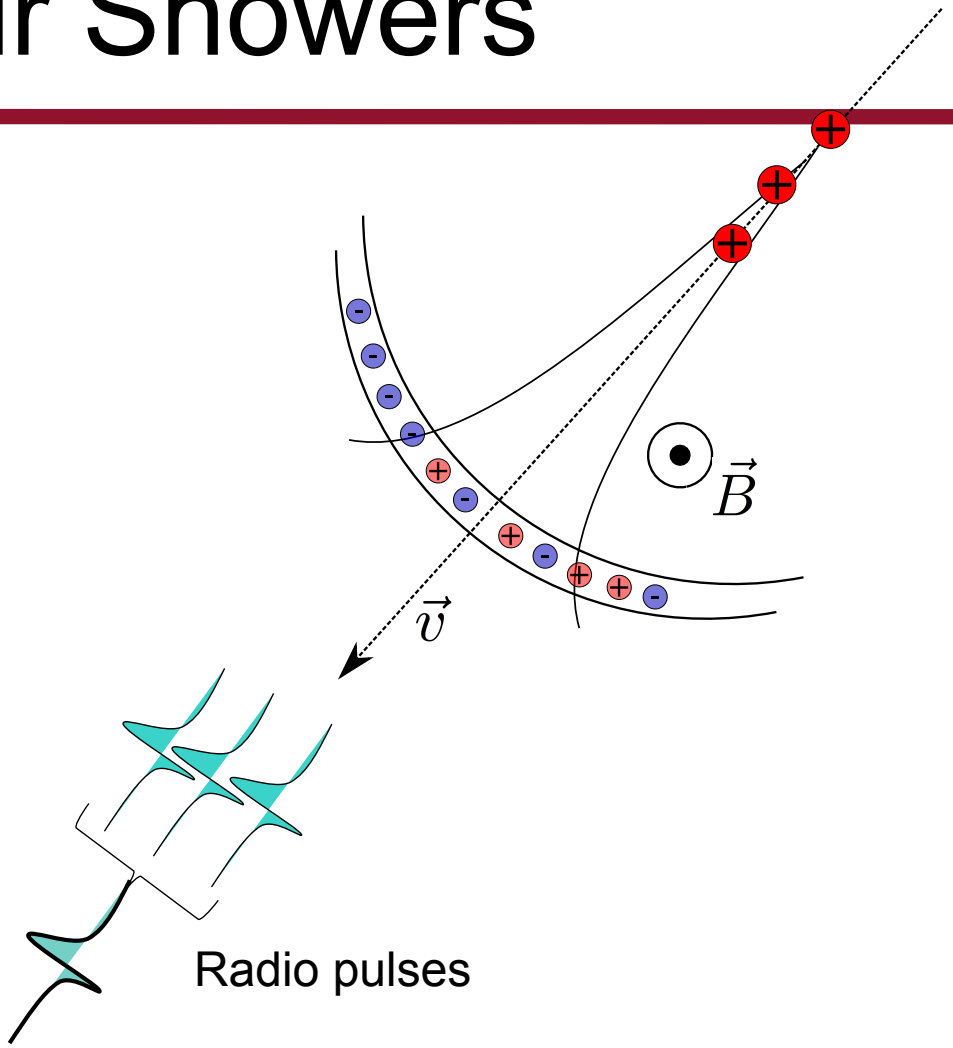


Berezinsky, 2013

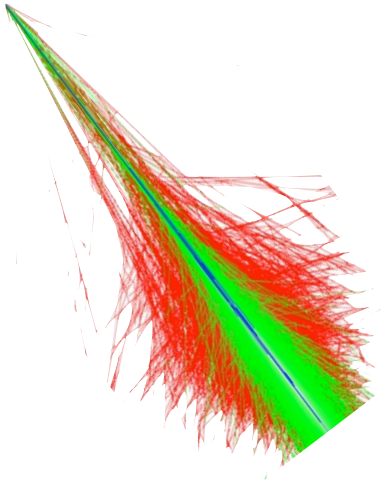
Measuring Air Showers

Central Core of LOFAR

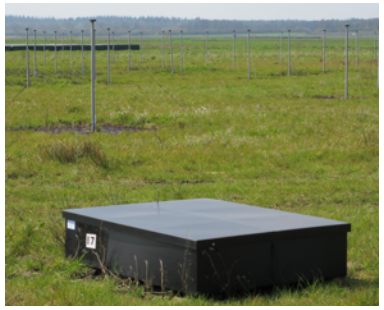


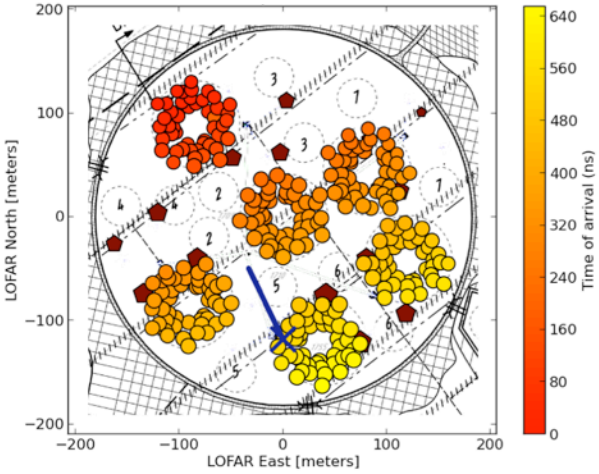


Measuring Air Showers

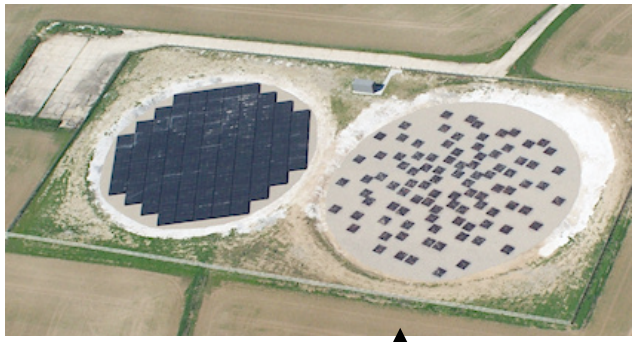


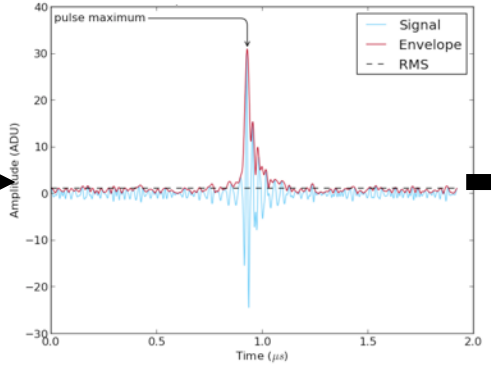
Trigger from LORA particle detectors





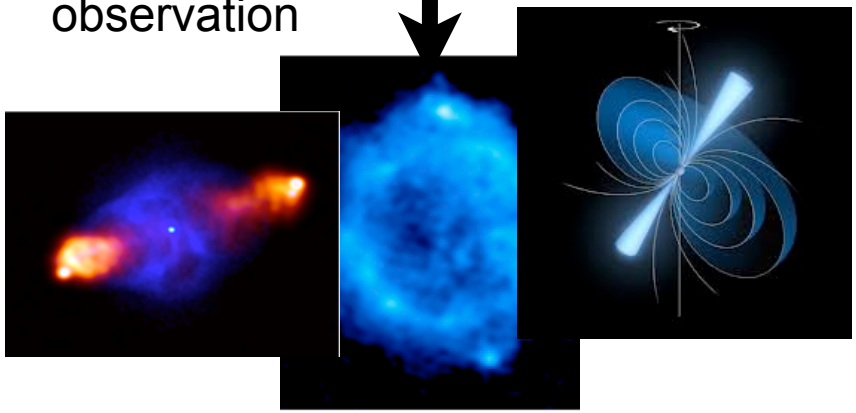
Read-out Buffers

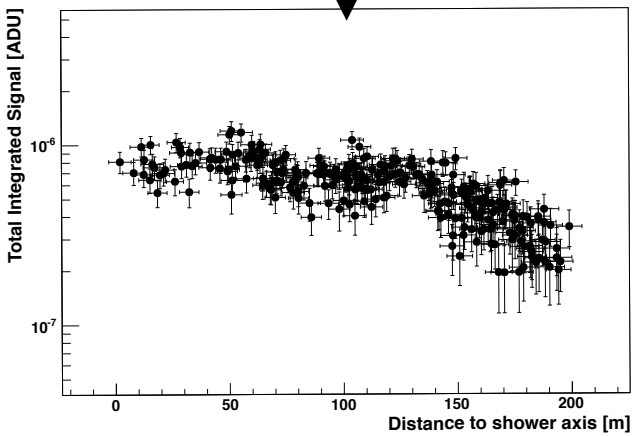




Analysis Pipeline
(Cluster at Nijmegen)

Ongoing observation

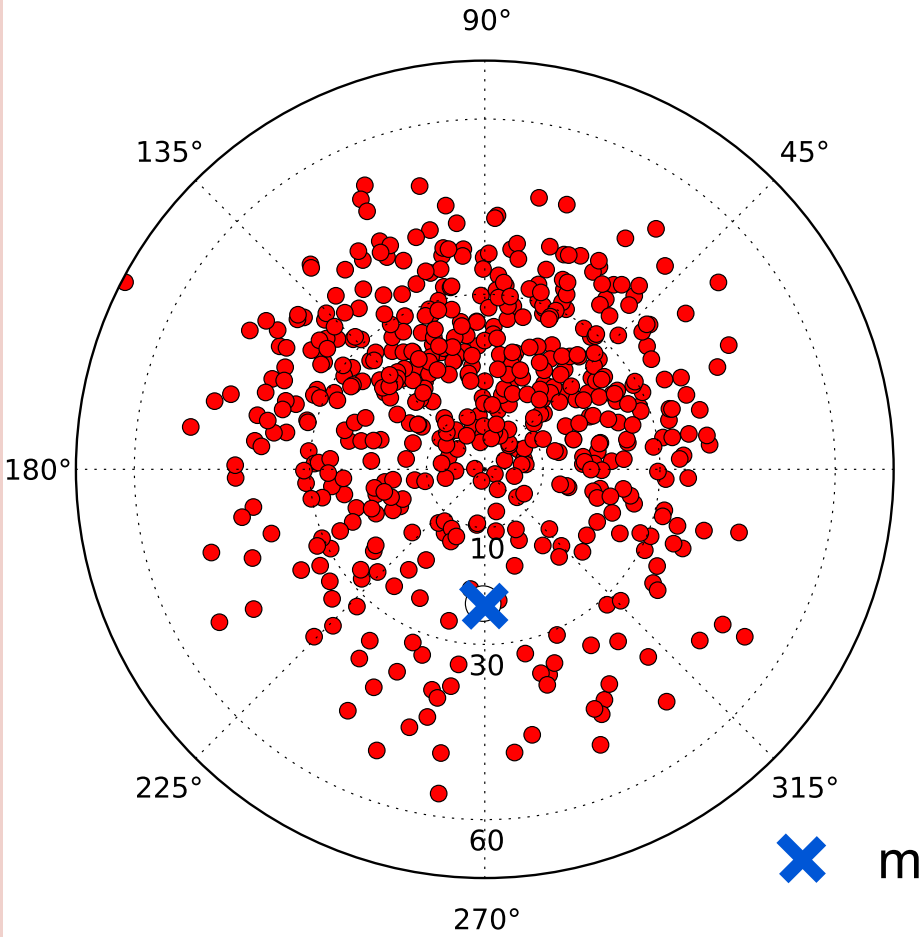




Power, Polarization, Timing per antenna

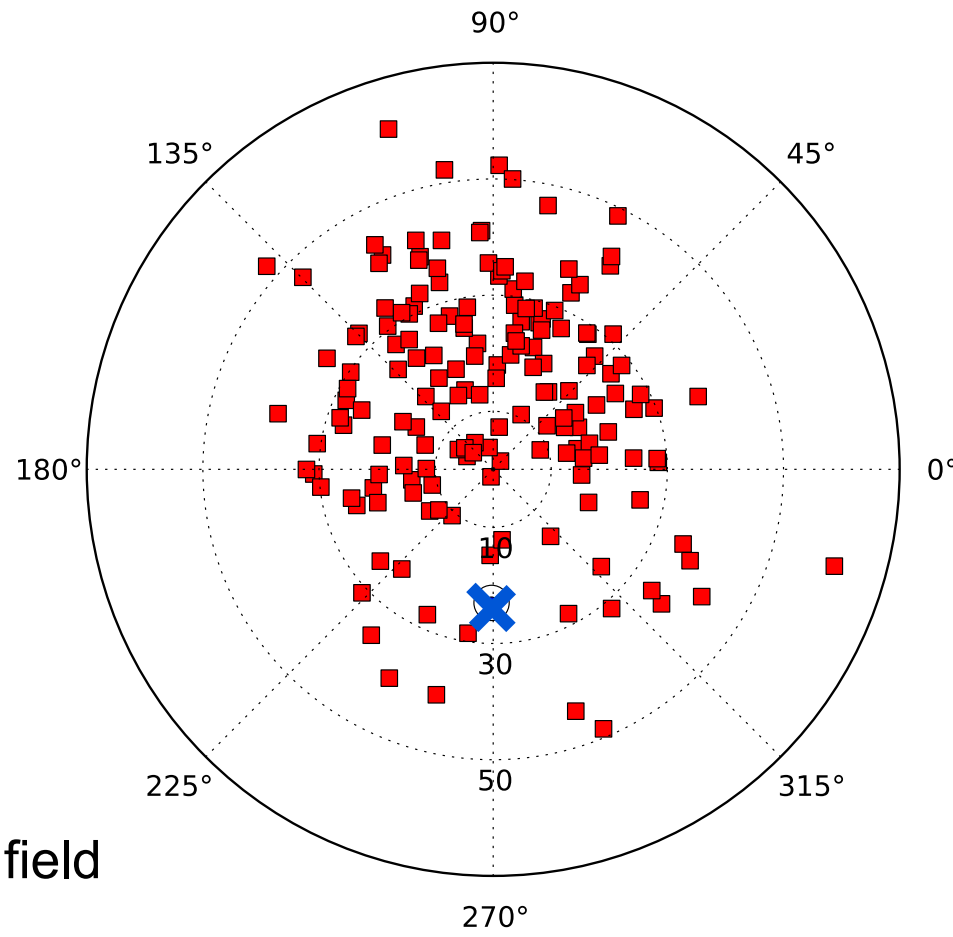
Detected air showers

LBA: 10 - 90 MHz



- low-band antennas
- main tool for analysis
- stronger signals expected

HBA: 110 - 230 MHz

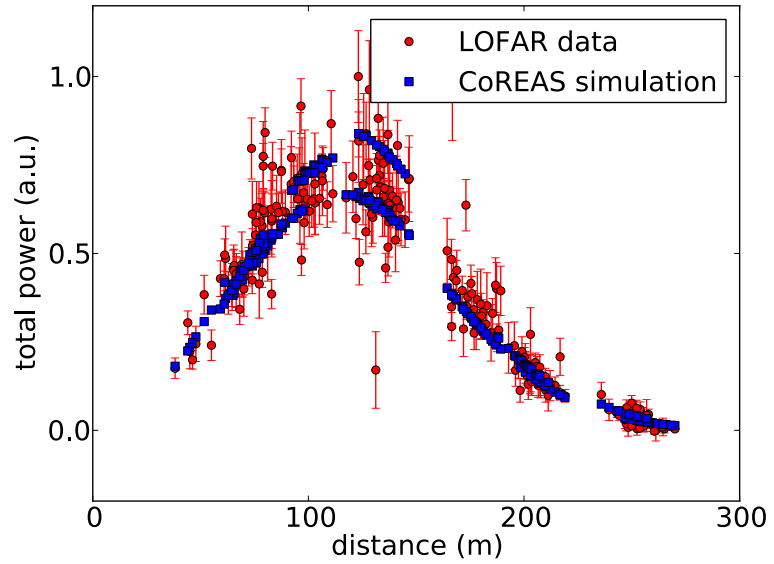


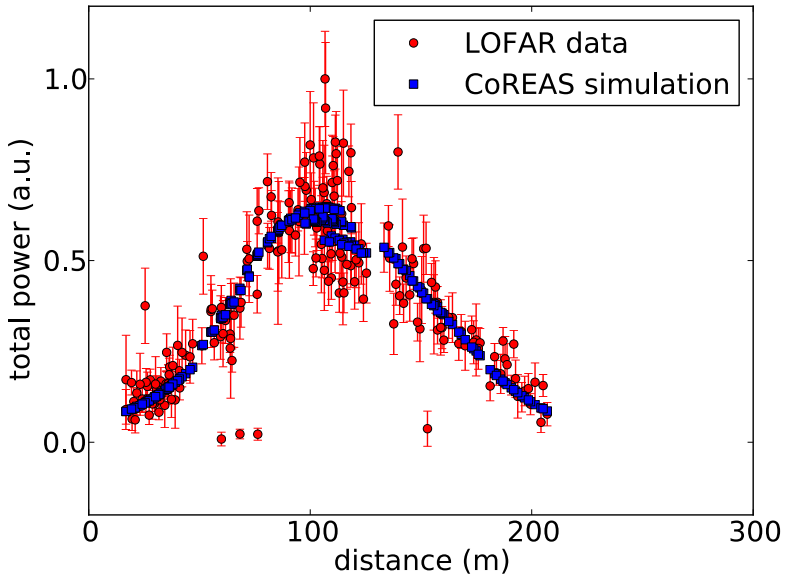
- high-band antennas
- smaller beam, less dedicated time
- only experiment in this frequency range

magnetic field

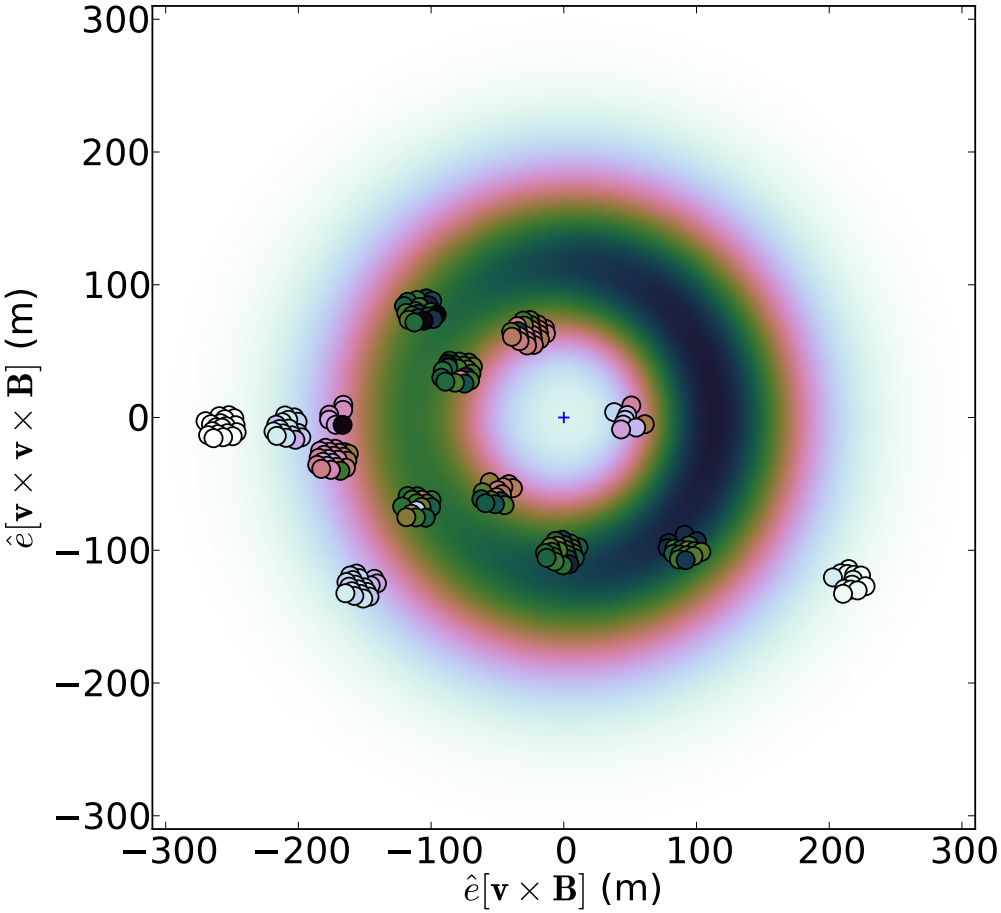
Measuring Cherenkov rings

Nelles et al, submitted to Astroparticle Physics





110 - 190 MHz

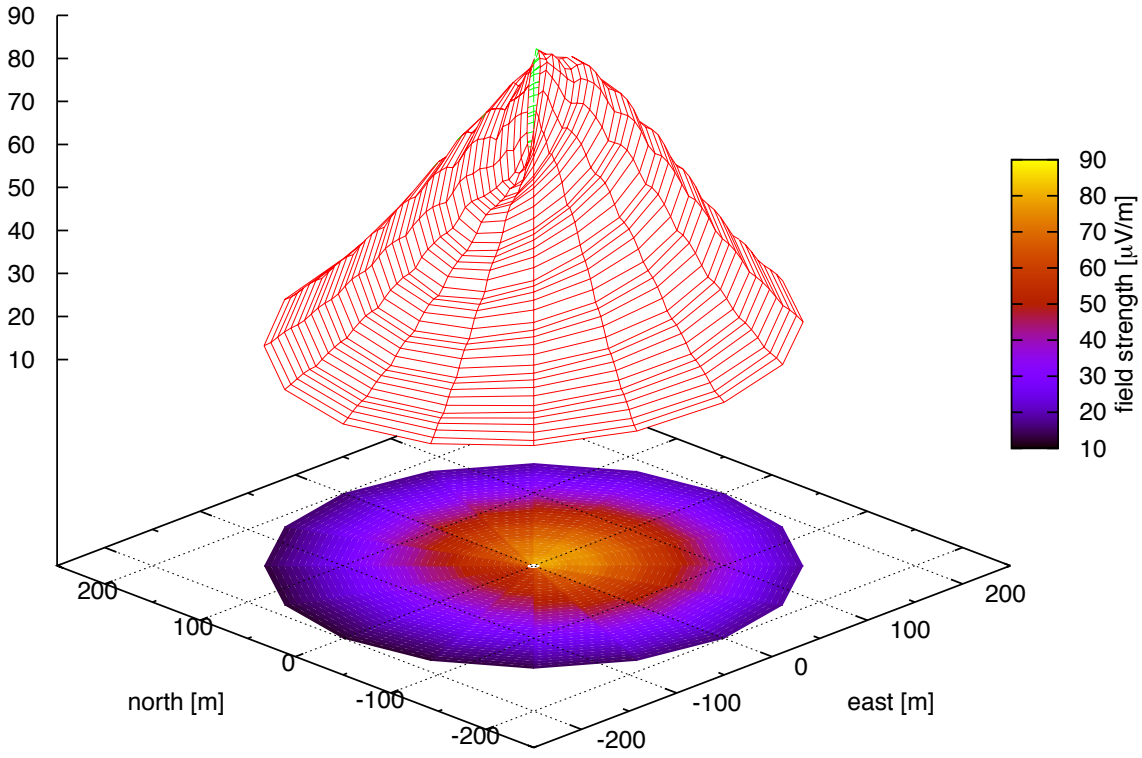


- higher frequency-range: dominance of relativistic time-compression
- first experiment to observe these in single events

More details: Using simulations

Simulations now describe the radio signal adequately:

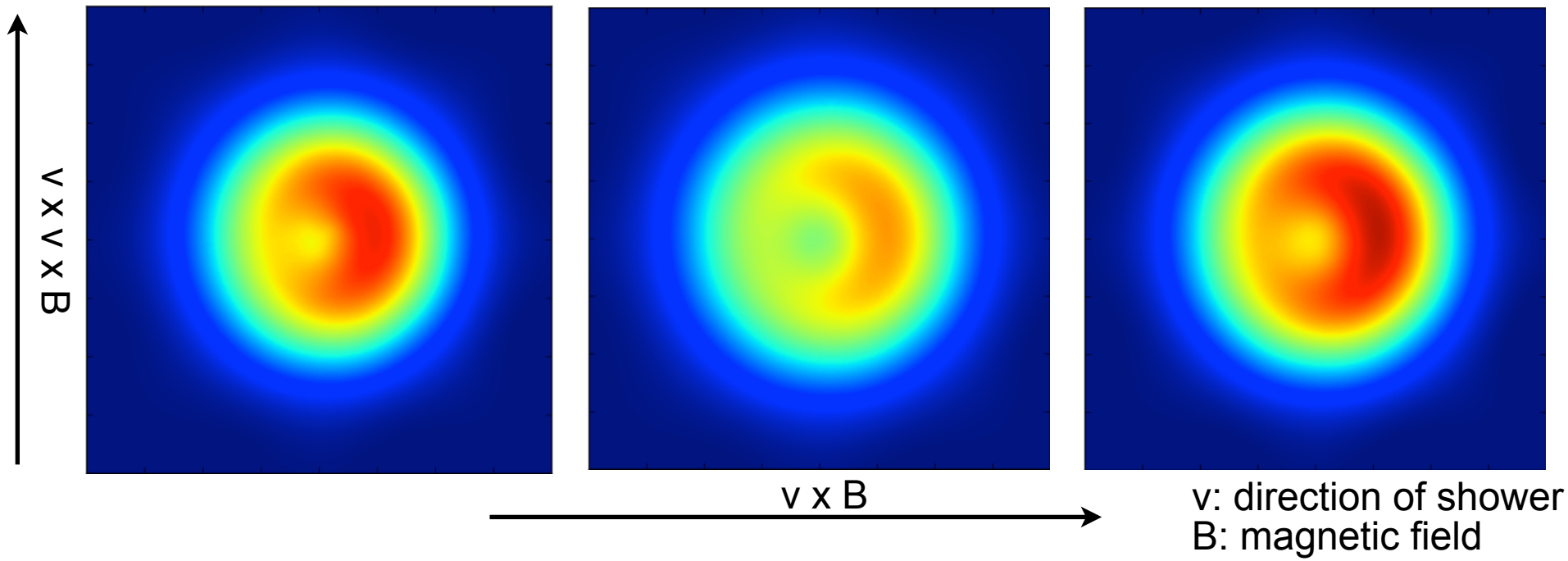
- based on air shower simulations, including a realistic atmosphere
- complex pattern in 2D
- asymmetry through interference of emission mechanisms with different directions of electric fields
  - geomagnetic effect
  - charge excess
- additional relativistic time-compression



CoREAS simulation, Huege et al. 2013

More details: Using simulations

Signal distribution (10-90 MHz) : same energy, same arrival direction, different Xmax

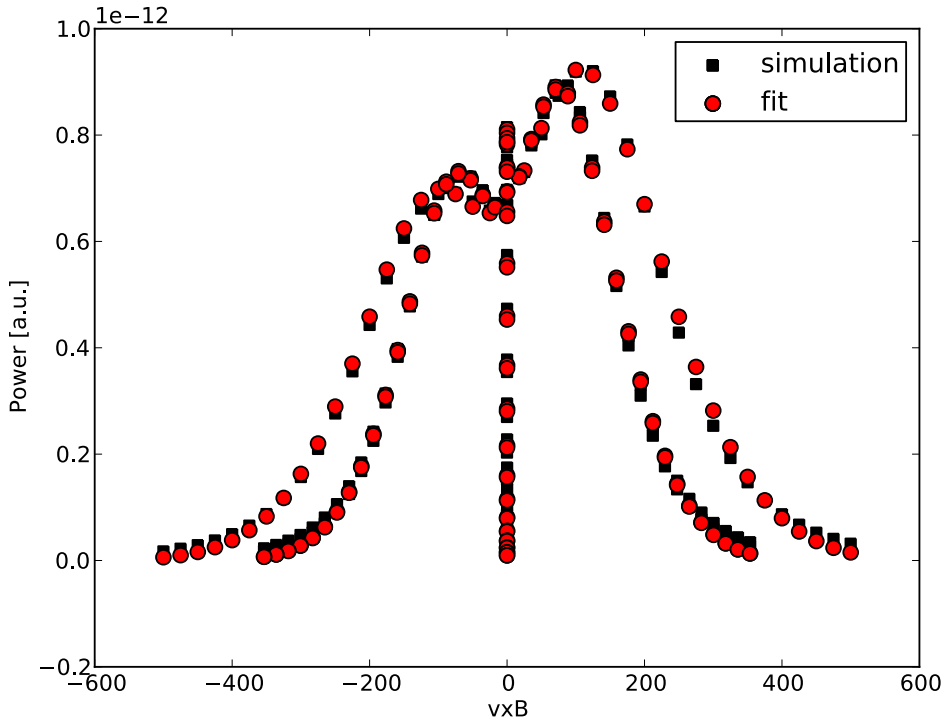


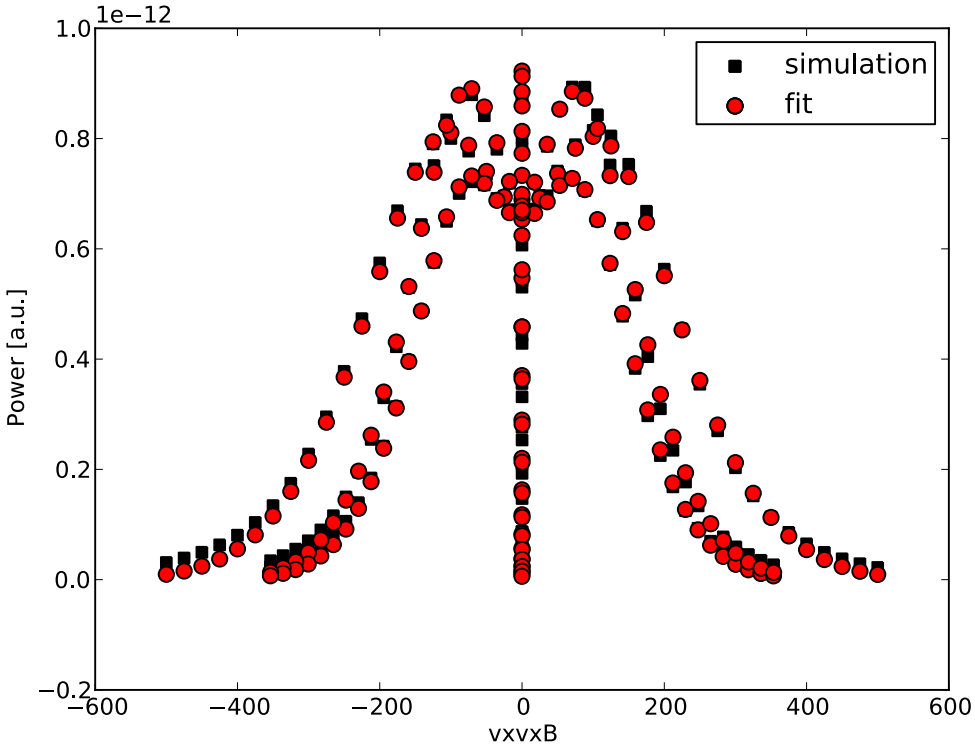
- Power pattern on the in shower plane strongly dependent on height of shower maximum
- **direct comparison to simulations: Xmax can be fitted per event** (Stijn Buitink, this session)
- One simulation > 1 week => parameterization to speed up process

Parameterization of the signal

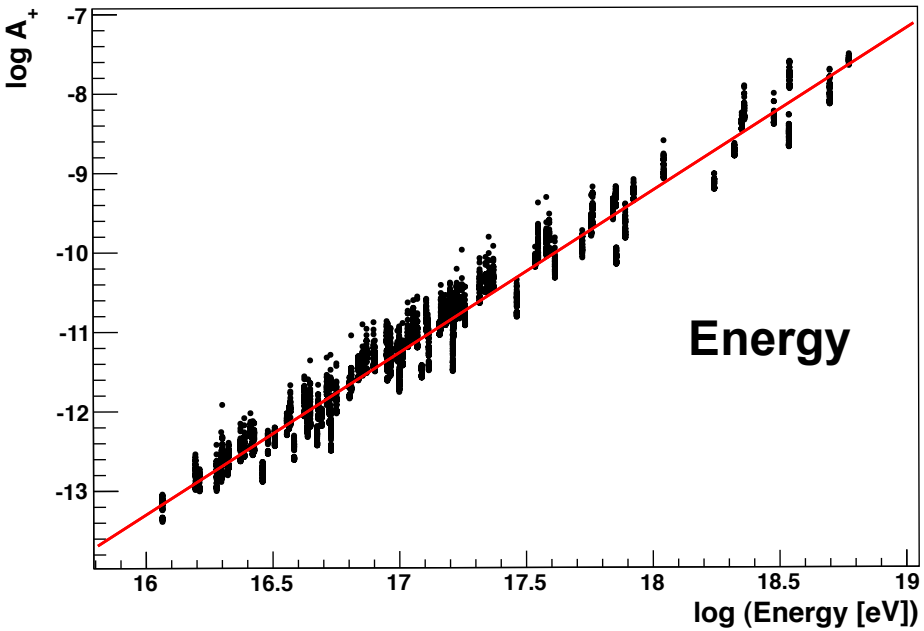
- From shape considerations: Gaussian + inverted Gaussian

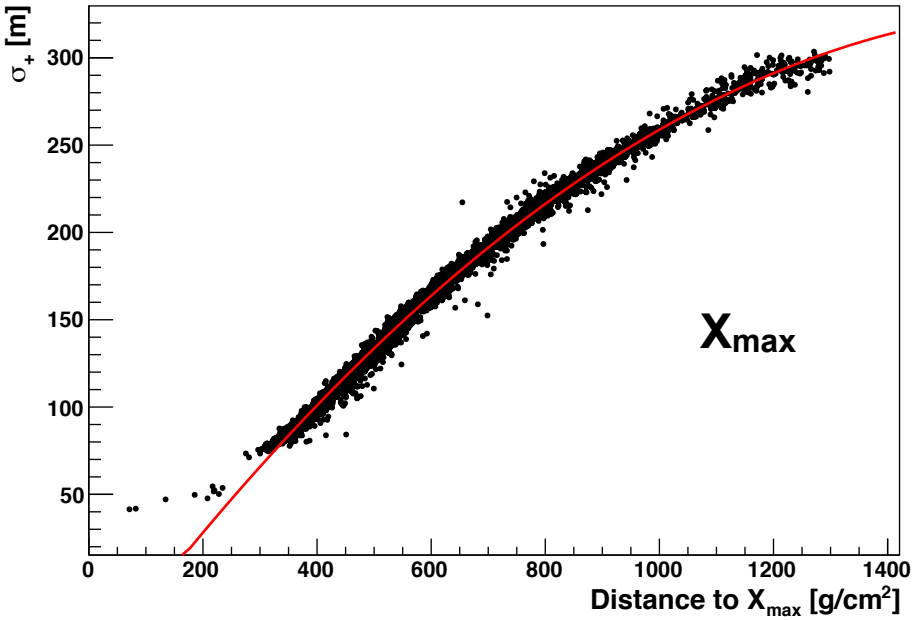
$$P = A_+ \cdot \exp\left(\frac{-[(x' - X_+)^2 + (y' - Y_+)^2]}{\sigma_+^2}\right) - A_- \cdot \exp\left(\frac{-[(x' - X_-)^2 + (y' - Y_-)^2]}{\sigma_-^2}\right) + O$$





Parameterization of the signal

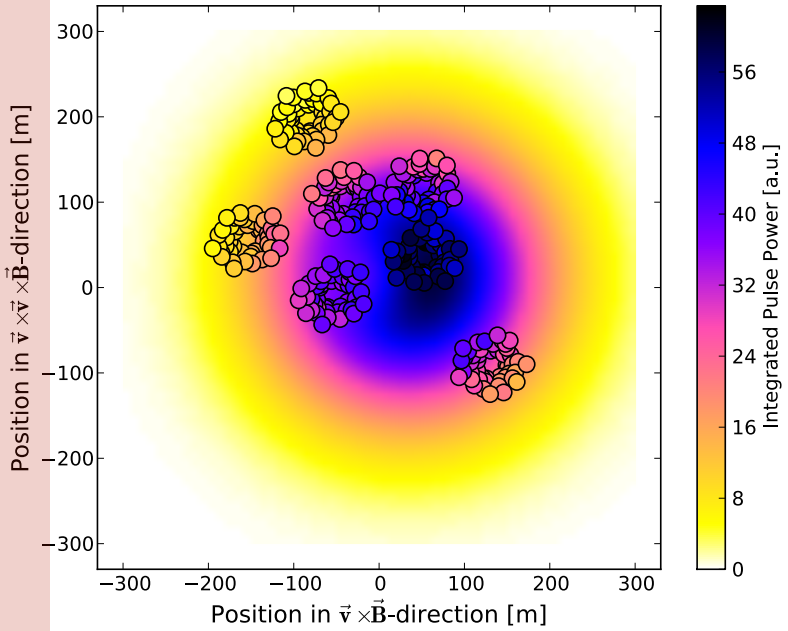


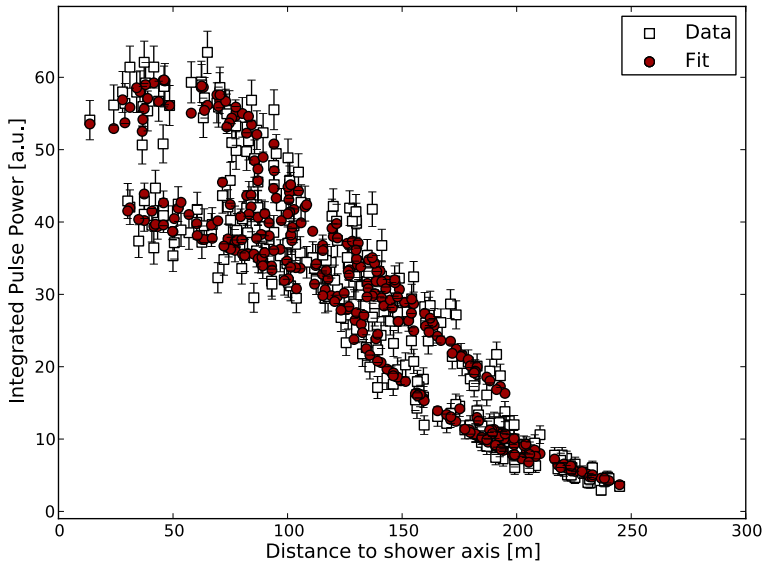


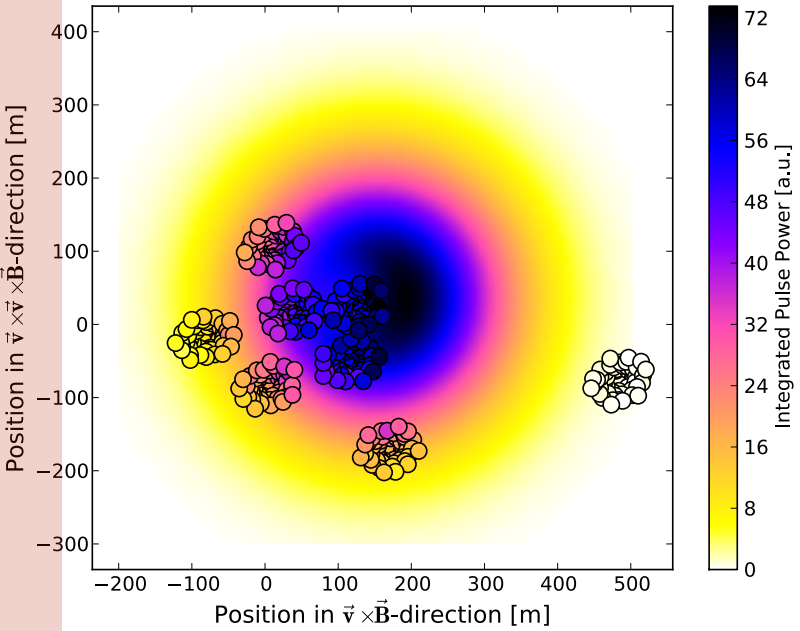
- All fit parameters relate to physical quantities:
  - Energy
  - Distance to the shower maximum, X_{max}
  - Influence of the interplay between emission mechanisms

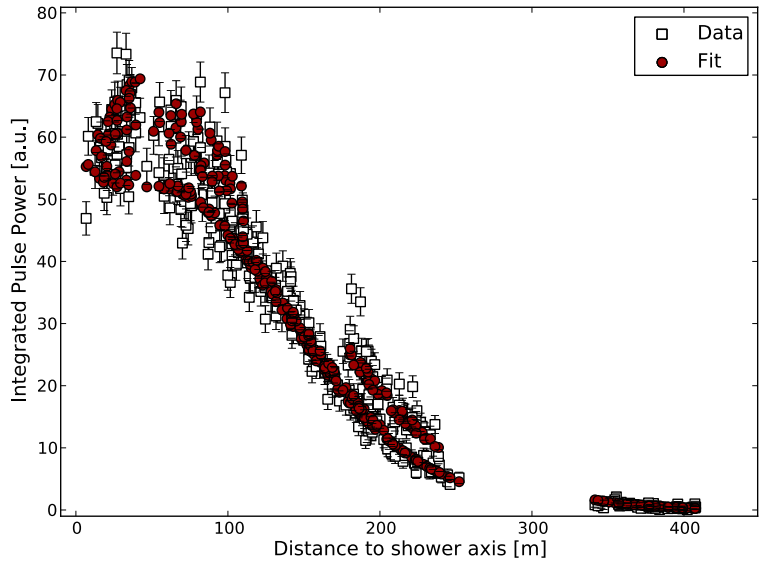
- very good handle on data analysis not requiring excessive Monte Carlo simulations

Parameterization of the signal









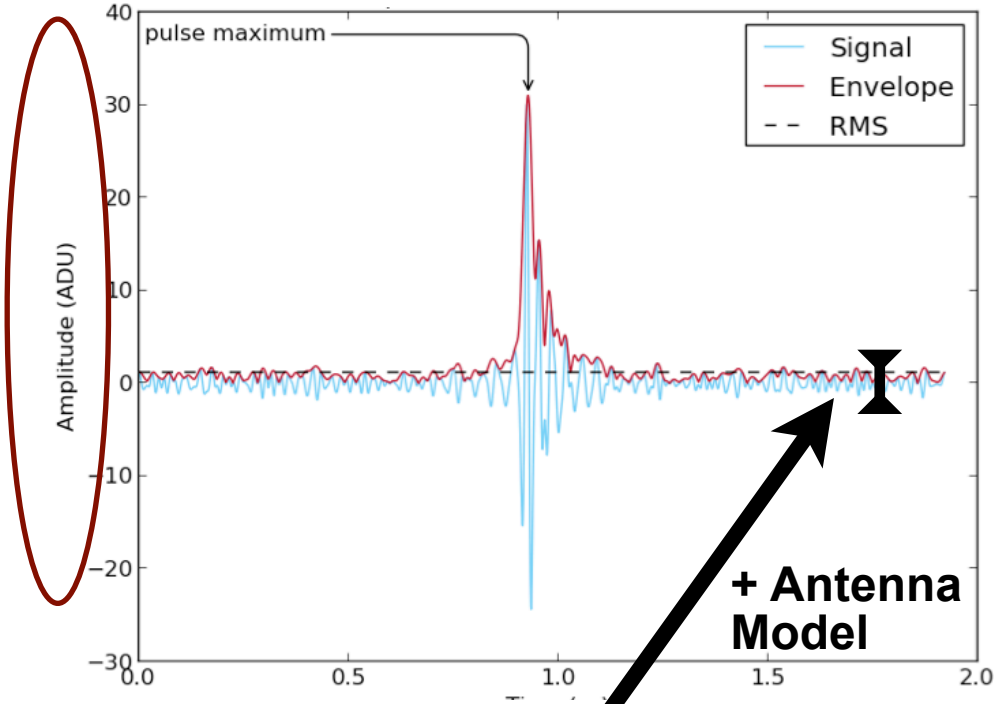
- All LOFAR data can be fitted by this function
- Exception: data taken during thunderstorms and non-cosmic ray pulses

Nelles et al, submitted to Astroparticle Physics, arxiv:1402:2872

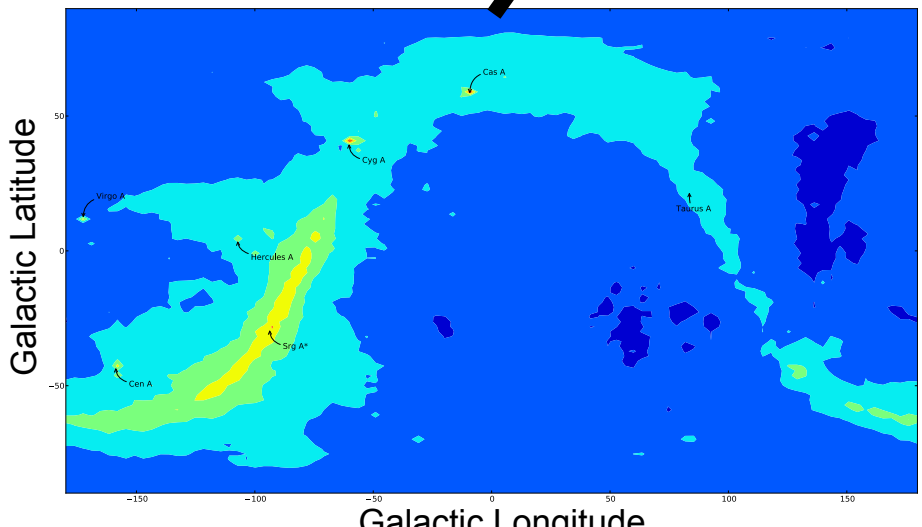
What is next?

Absolute Calibration (LBA)

- V/m instead of ADU
- cross-calibration campaign in the field scheduled May 2014
- in cooperation with other experiment
- “dominant noise is the Galaxy”
  => RMS of voltage traces can be predicted



+ Antenna Model

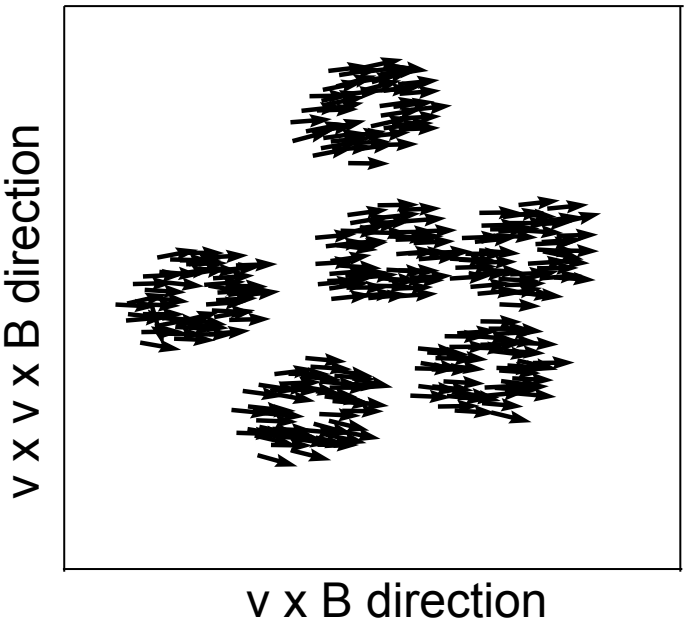


Understanding the antenna model

Directional Dependence

- current antenna model reconstructs direction of measured electric field accurate for polarization studies with cosmic rays

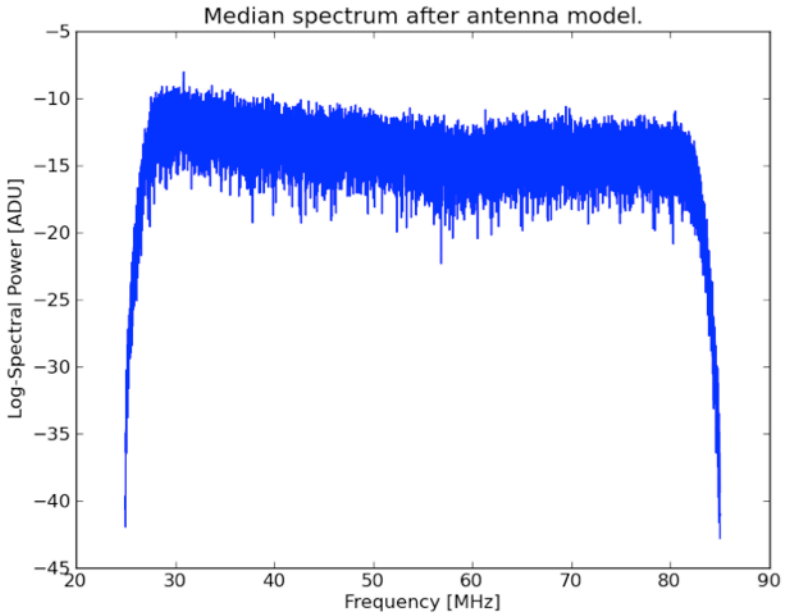
- Polarization in v x B expected
- Reconstruction confirms this



Frequency component

- resonance frequency at observed position

- spectrum not fully flat, slight discrepancies observed



Conclusions

- Successful **measurements of air showers** with LOFAR since June 2011
- First detection of Cherenkov ring at 110-230 MHz
- Data-set delivers excellent results
- Signal in LBA can be parameterized using a double Gaussian with 5 parameters:
  - position of on ground
  - scaling factor ~ energy
  - width or slope factor ~ shower maximum
  - offset factor
- Antenna model now more reliable
- Absolute calibration planned